

SNOW COVER AREA CHANGE IN THE VOLCANO “EL ALTAR” IN ECUADOR USING  
LANDSAT IMAGES

by  
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## **Abstract**

In Ecuador, the loss in snow cover area, can severely affect agricultural lands, protected areas and people's access to clean water. I investigated the changes in snow cover in the Altar volcano in Ecuador in the last thirty-nine years (1979-2018) and used regression modeling to explore how monthly average precipitation and temperature influences the snow cover fluctuation.

Snow coverage was measured using three separate approaches. I found that snow cover declined in both wet and dry seasons; dry season values decreased from 15% to roughly 7%. Models explained roughly 20% of the variation in snow cover suggesting that complications from ENSO events may have large impacts on El Altar.

The results of this project underscore the need to design and implement policy that will allow the communities downstream to mitigate and adapt to the consequences of climate change.

## Foreword

The culmination of this Capstone Project has been the realization of a long-kept dream; a dream that came into my mind several years ago during a winter storm. Stuck in my home in Denver, I profoundly longed for the Andean Mountains of my childhood.

Fast forward a few years, and I found myself as member of one of the most prestigious universities in the world. My love for the Andes is now accompanied by the knowledge I have acquired during my tenure at Johns Hopkins University. My commitment to protect natural resources is even stronger because I have some of the necessary knowledge needed to find solutions. The classes I have taken during the pursue of my Masters in Environmental Science and Policy, have been the base and inspiration to this project. Offering a concomitant certificate of GIS provided me with the tools which, combined with the scientific basis, have resulted in the successful conclusion of this Capstone Project.

This project presents an easy, compelling, and relatively fast way to estimate the loss of snow cover areas. This simple technique can be applied to any snow-covered mountains not only in the Andes but worldwide. This project is an example of the potential that Remote Sensing has on studying the areas that are almost, if not completely, impossible to study in-situ. This method can also provide an easy visualization tool that can be brought up in front of any policy makers, interest group, or the public, to allow for their understanding of the threat of snow cover loss. This visualization can be presented with or without the temperature and precipitation components, if is not desired or unpractical to talk about the drivers of the snow cover loss and go directly to the issues of how to adapt and mitigate the effects. Thousands of people depend on our capacity to explain the solutions.

## **Acknowledgments**

I would like to first thank my Capstone Advisor, Professor Rodolfo Dirzo, of the Department of Biology at Stanford University. Prof. Dirzo's work inspired me pursue a subject important to me. Knowing that someone with my similar background can achieve so much professionally, has given me courage to continue pursuing a career in Conservation. Prof. Dirzo's kind and honest advice and feedback have been of incredible value to the successful completion of this project.

I would also want to thank my dear friend, Susan Buckingham PhD, for providing honest advice and input. Doctor Buckingham was always open to hear my ideas (even the most irrational ones), and to provide perspective. She steered this project in the right direction more than a handful of times. This project could not have been successful without Doctor Buckingham's support.

I would also like to acknowledge Professors Daniel Zachary and Nicole Cosey from Johns Hopkins University, for their feedback and for reviewing earlier drafts of this report. Thanks to Stephen Chignell, Department of Ecosystem Science and Sustainability at Colorado State University, for his feedback on the design and methodologies used for this project. Thanks also to Sofia Linn of the Spatial Centroid at Colorado State University for providing me with contacts and resources important to this project.

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## **Introduction**

The present study focuses on Ecuador, one country of special significance in terms of biodiversity and the challenges such biodiversity faces in light of current global environmental change. The country of Ecuador is located in South America, between Colombia and Peru. It is bisected horizontally by the equator and vertically by the Andean Mountains. It has a great variety of ecosystems due to the diversity of climatic conditions, shaped by the dramatic changes brought about by the country's altitude gradient and its closeness to the equator (Jorgenses, Ulloa and Maldonado 2006). The coast is mostly tropical, becoming colder inland as elevation increases, and warm again at the lower elevations of the Amazon region east of the Andes. Although is a rich country in terms of biodiversity and natural resources, about 41 percent of its populations live on less than \$1 a day and about a similar percentage lives below the poverty line (Hentschel et al. 2018). Poverty is a large driver of environmental destruction. In the last few years, the Ecuadorian government has increased its investment in the tourism industry, especially ecotourism, sustainable agricultural practices and tougher environmental regulations (Gilles et al. 2017). These strategies aim at increasing income that can be in turn redirected to conservation projects, or at least not to disrupt already environmental-friendly private business. Large internal migration has forced people towards cities and about 55 percent of the population lives in urban areas. Ecuador has substantial petroleum reserves in the Amazon region. The Ecuadorian economy is heavily dependent on the export of oil and agricultural goods. About 50 percent of all the country's earning comes from the oil industry (Gilles et al. 2017). This dependency on oil makes the country very vulnerable to the fluctuations on the world prices. An exploitation-based economy, lack of environmental regulation and enforcement of the laws that

do exist, are deemed to be the major reasons underlying the environmental issues in the country (Asfaw et al. 2018). Although Ecuador is not a major contributor in the greenhouse emission worldwide, climate change and resource depletion associated with poverty and population growth, put the country in a difficult position to find adaptation and mitigation strategies to combat the effects of climate change (IPCC 2014).

The retreat of the snow cover in the Andean mountains of Peru, Chile and, Ecuador has been documented in the recent literature (La Frenierre and Mark 2017; Stigter et al. 2017), and it has been found to be strongly correlated to variables of climate change (La Frenierre and Mark 2017), which consequently threatens with altering the water cycle of the area. Changes in snow cover total area affect water storage and runoff down in the catchment because snow cover can act as a temporal water storage for the rain falling as snow at high elevations (Chevallier et al. 2014). Climate change can significantly diminish the Ecuadorian water stocks. (Bendix et al. 2011). Snowpack also provides soil moisture and ground water replenishment (Sospedra-Alfonso, Melton and Merryfield 2015). With the high vulnerability of the country to the disruption of agricultural outputs, climate change poses an imminent threat to the economy and socio-ecological stability of the country (La Frenierre and Mark 2017). Empirical observations of the Andes in Ecuador already show a decrease in the snow cover of all the mountains in the Region <sup>1</sup>. Several studies have measured the sensitivity of snowpack to temperature and rainfall by studying not only snow cover area, but also glacier depth and movement (Sospedra-Alfonso, Melton and Merryfield 2015, La Frenierre and Mark 2017, Asfaw et al. 2018). Ideally, similar

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<sup>1</sup> This statement is based in personal observations as well as observations of several people (friends, family and foreigners) who have lived these areas for several decades.



studies should be conducted in different locations of the Andean Region, in order to acquire a more complete assessment of this phenomenon of snow coverage reduction in South America. By collecting, analyzing and comparing historic Landsat images of the Volcano “El Altar” in Ecuador, this project aims at finding changes in the size of the area covered by snow based on data spanning a period of about 40 years. This time frame would be sufficiently long to stablish a trend and was chosen based on image availability. Based on the literature about what other similar projects have found for this area, I aimed at quantifying the decrease in snow-covered area. Also, as important as identifying spatial and temporal changes in snow cover in the Altar Volcano, is to examine the relationship between those trends and precipitation and temperature, using data collected over the last few decades (La Frenierre and Mark 2017). The specific questions I seek to answer with this project are: i) what is change in the Altar Volcano’s area of snow cover over the last few decades? and ii) is there a correlation between the changes or trends in snow cover and temperature and precipitation? The answers to the questions posed in this project are significant because they can inform policy and may result in immediate responses to climate change.

## **Project background**

Historic Landsat images have been used to estimate the extent and spatial trends of clean snow cover area in many areas of the world (Stigter et al. 2017; Mishra, Babel and Tripathi 2013; La Frenierre and Mark 2017; Duran-Alarcon et al. 2015). The analysis of snow cover has been used before as a preliminary step to assess the quality of water resources (Stigter et al. 2017; Linde and Grab 2011). The first Landsat satellite was launched by The National Atmospheric and Space Administration (NASA) in 1972 (Young et al. 2017). Since then, satellite imagery has

become the most commonly used tool to assess the trends and current state of the mountain snow cover because in situ observations of snow are logistically challenging, expensive, less reliable (depending on the specific project), and time consuming (Duran-Alarcon et al. 2015; Poveda and Pineda 2009). Hyper-temporal remote sensing responses have been proposed as a tool to provide insights on the variability of snow cover in ecological sites by using the quantification of the “temporal response of land surface spectral properties” (Maynard and Karl 2017, Duran-Alarcon et al. 2015). Many studies use remote sensing with in-situ observations and compare their results with surveys such as the Gridded Soil Survey Geographic database (Maynard and Karl 2017, Poveda and Pineda 2009). The most complete results are produced by projects using *in-situ* data in concomitance with remote sensing to provide validation, to increase accuracy and allow to collect samples and measurements that are not possible to get from remote sensing alone (such as snow depth) (Poveda and Pineda 2009; Duran-Alarcon et al. 2015). Remote sensing can still be useful for areas where *in-situ* collection is not possible, either for logistical, or financial reasons (Zhu 2017). In the particular case of this project, the limited time available to complete the study, plus the lack of funding did not allow for *in-situ* data collection. My hope is to continue with this project and to complement it with some *in-situ* data in the future.

Correlations between global warming and decreases in snow cover have been found in several areas of the world by using temperature and rainfall data (Poveda and Pineda 2009; Duran-Alarcon et al. 2015). Several studies on mountainous regions like the Andes or the Rocky Mountains, have found a direct relationship between changes in snow cover and local climate and hydrology (Sospedra-Alfonso, Melton and Merryfield 2015). The Ecuadorian government, in collaboration with The World Bank, has recognized the importance of climate change

research. Historical precipitation and temperature are now freely available and ready to download from the Instituto Nacional de Meteorología e Hidrología (INAMHI). The downloadable datasets contain average precipitation data from 1901 to 2015 (2016 became available during the writing of this report), by monthly and yearly averages. These data can now be readily used to assess possible drivers of snow coverage change.

## Study site

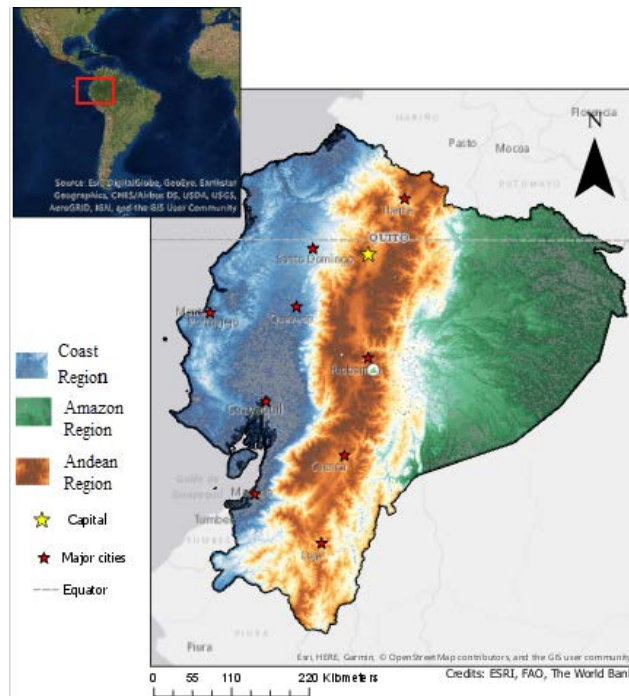
Ecuador has three main natural climatic regions: Pacific Coast, Andean Mountains, and the Amazon Rainforest (the Galapagos Islands are often considered a fourth region).

However, Ecuador's position in relationship to the equator and its dramatic changes in topography, throughout the country, create the microclimates responsible for the great biodiversity of the country (Fig. 1). These sub regions can be quite different from one other, but none of them have four seasons.

Instead, Ecuador has a wet and dry season

and the country also enjoys of about twelve hours of sun light year around.

The volcano Altar, located about 170 Kilometers south from the capital city of Quito, is part of the Occidental range of the Andean mountains (Fig.1). The total area encompassing the Altar is mostly located in the Chimborazo Province in central Ecuador. A small portion of the area of the

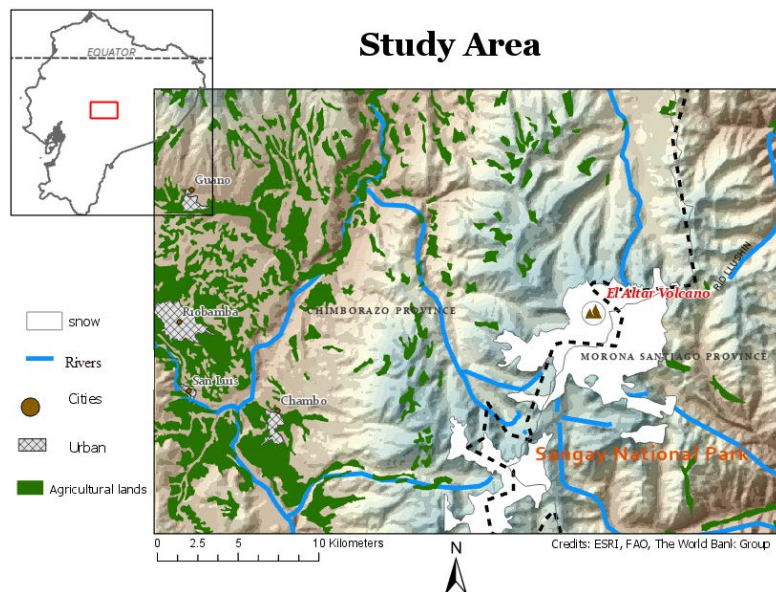


**Figure 1:** Ecuador showing the three natural regions, and major cities. This figure also shows El Altar in relation to the equator.

volcano is in the Zamora Chinchipe Province, which is mostly part of the Amazon region and therefore has a much lower elevation. Altar sits between two different regions, corresponding to the Chimborazo and Zamora Chinchipe Provinces.

The Chimborazo province has a growing population of about half a million people, most of who obtain their drinking water directly from the Altar's snowmelt (without previous

sanitation) (INEC Ecuador 2018). In this region, about 32% of men and 36% of women work as farmers (INEC Ecuador 2018). The agricultural area below the volcano has an extension of about 3,354 km<sup>2</sup> (Mendieta Muñoz et al. 2015) and produces corn, potatoes, green beans, lentils, onions and quinoa. Farther away from the volcano, in lower elevations (closer to the coastal region), the Chimborazo province produces coffee, plantains, sugar cane, oranges, lemons and limes. The Chimborazo province takes its name from the Chimborazo, the tallest mountain in Ecuador (6310 m a.s.l.). With an average temperature of 13 °C, the Chimborazo province has ecological zones ranging from alpine (3000 m a.s.l. and higher) to dry subtropical forest (about 1000 m a.s.l.). The Altar is in the “cordillera occidental” where higher peaks are found. As the other volcanos in the region, The Altar is a stratovolcano, but unlike other volcanos in the area,



**Figure 21:** Closeup of the area surrounding the Altar. Volcano is in the border between the Chimborazo and Morona Santiago provinces. Several towns are located on the West side of the volcano while the Sangay National Park is located on the East.

The Altar is no longer active. The Altar is formed of nine major peaks, the highest of which is about 5,330 m a.s.l. (Rosqvist 1995) and one of the most difficult climbs in Ecuador, requiring high technical skills and equipment (Ministerio de Turismo de Ecuador 2018). Since runoff is available throughout the year, this volcano is an important water reservoir for the agrarian communities who live at its foothills. Some of them are as close as 30 Km (Fig. 2). The Altar is also located within the limits of the Sangay National Park, created in 1975. The Sangay National Park is the home of about five hundred species of vertebrates, 345 of birds, 100 mammals, 25 amphibians and 14 reptiles. Most impressive in the plant diversity of the area, with more than 3000 species of plants. The preservation of the water resources from The Altar is also important to the biodiversity and ecosystems health of the whole park.

### **Climate**

As mentioned before, Ecuador's climate is heavily influenced by two determining characteristics: distance from the equator and elevation gradient. However, other cyclic atmospheric events, such as El Niño, disrupt regular patterns of temperature and precipitation. The Pacific coast of Ecuador experiences El Niño events, as increased temperature of the ocean warms the waters. Ocean waters warming increases precipitation in the coastal region or further into the mainland depending on the intensity of that year's event (Bendix et al. 2011). During El Niño years, the spatial-temporal variability of atmospheric circulation processes is altered in the whole country, but the Pacific coast and the east side of the Andes are the most affected (Serrano-Vicente et al. 2017). How much this affects precipitation in the mountain range is still not completely clear. However, while some researchers believe the impact of El Niño is limited to the western edge of the Andes, others have found a connection between El Niño and changes

further into the mainland. In a paper written by Rodwell et al. (1999) researchers documented how sediment records obtained from the Laguna Pallcacocha, located at 3,000 m.a.s.l. in southwestern Ecuador, correlated with patterns of storm-induced increased sedimentation. These patterns tell the story of increased rainfall and drought which seems to coincide with El Niño events. The authors argue these sediments are evidence of increased frequency of El Niño and effects at higher elevation (Rodwell et al. 1999). The warming of the Pacific Ocean near Guayaquil (on the coastal region, Figure 1) is one of the first signs of the onset of El Niño. Most of the coastal region precipitation increases are due to the onset of strong or very strong El Niño years. Studies have found that the intensity of the Walker Circulation—a model of air flow loop in the tropics at in the troposphere also called the overturning cell—is different during El Niño events.

### **Rainfall**

Variations in climate regimes across Ecuador are largely due to variations of precipitation. For example, rainfall in the eastern slope of the mountain is generated by the wet easterly trade winds coming from the Amazon region and the Atlantic Ocean. In the northwest rainfall influences the intertropical convergence zone which brings moisture from the Pacific Ocean. Increasing elevation forces this moisture, producing rainfall on the west side of the Ecuadorian Andes. In contrast, moisture along the southern slopes is produced by the Humboldt current, which brings cold air from the south and runs along the South America's western coast. As a result, the east side of the Andes has a much lower annual average rainfall than the west slope (a rain shadow effect). Although Ecuador does not have the seasonality of higher latitudes, rainfall is highly dependent on seasonality. Seasonality is also dependent on the specific region (different

months may be considered to be in the dry or wet season depending on the specific area and how close that area is to the equator). Ecuador's inter-Andean region, where El Altar is located, has a rainy season from October to May and a dry season from June to September (Climate Change Knowledge Portal 2018). Due to the location of the Altar, it is likely that its weather is relatively equally influenced by the Pacific system (western slope) and the Atlantic systems (eastern slope).

### **Temperature**

Temperature of specific areas of the country is relatively steady and the most drastic changes are observed during the morning hours versus mid-day. In some high elevation areas, the difference between day and night temperatures can exceed 20 °C, but the monthly variation is not very pronounced. Due to this lack of variability, snow cover at the top of the Andes does not change as drastically as in other areas of higher latitude. Seasonal changes, however, do increase water runoff, (Chevallier et al. 2014; La Frenierre and Mark 2017; Linde and Grab 2011).

## **Methods**

### **Software**

The USGS requires users to create an account and to download the Bulk Download Application (Version 1.3.6) to access Landsat images. 7ZIP was used to decompress those images before they were corrected and analyzed using ENVI 5.5 from Harris Geospatial Solutions. The shapefile polygons were also created in ENVI and further analyzed using ESRI's ArcGIS Pro. Shapefiles files and the portrayed maps were also done in ArcGIS Pro. Statistical analysis was performed in Minitab 18.

## **Image collecting and preprocessing**

The images used for this project are Landsat from USGS EarthExplorer's website. I used geotiffs in 30m pixels with UTM 17S in WGS 84. Two types of Landsat products were used: Level-1 and level-2. Level-2 were chosen. Level-1 products are created by using the best level available to the image, but still require certain level of pre-processing to optimize analysis (U.S. Geological Survey 2018). LandsatLook images are optimized Level-1 products at full resolution that are compressed and stretched to allow for better image interpretation, but are not recommended for the use in computerized image analysis. Both, regular Level-1 and LandsatLook images were used for this project. The preprocessing of the Level-1 images was based on the recommendations by Young et al. (Young et al. 2017). The images were first corrected for at-sensor radiance and Top of Atmosphere (TOA), which in turn corrects the images for atmospheric interferences (such as dust and gases) and therefore improves the accuracy of the analysis (Young et al. 2017). Level-2 images were chosen when Level-1 were not available.

## **Snow area delineation**

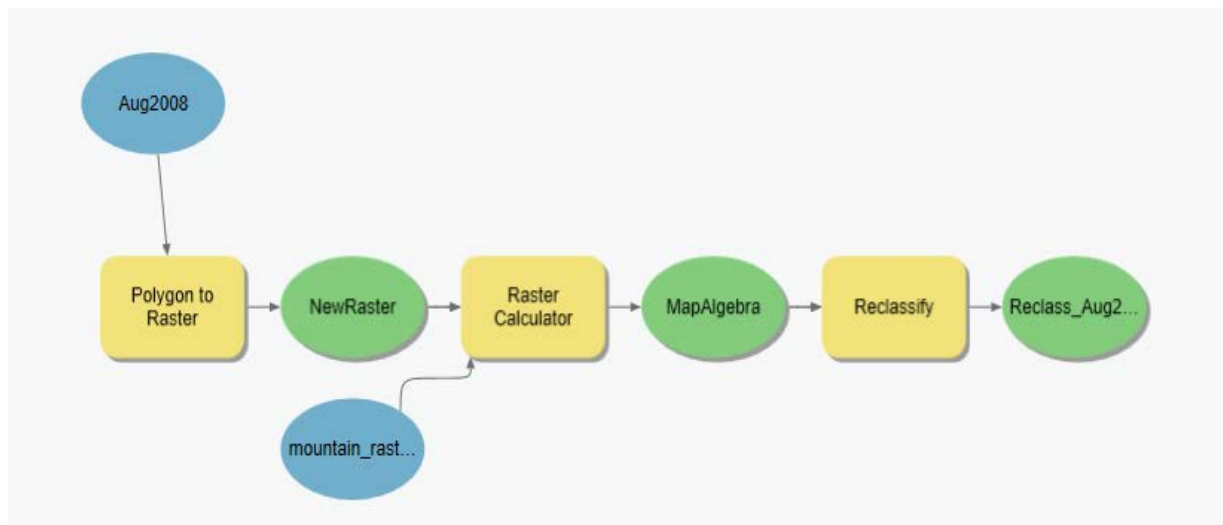
Once an individual image was downloaded into ENVI, I drew a polygon by carefully delineating the area of snow cover. To aid with this process, and to increase accuracy, each image had to be viewed using different band combinations. The combination of the different bands, which make up the image, allows for the desired feature to be more conspicuous.

## **Planer snow area calculations**

The snow cover shapefiles required additional steps to calculate the planer area. ArcGIS calculates area by creating an envelope around the complex polygon. The crescent shape of snow



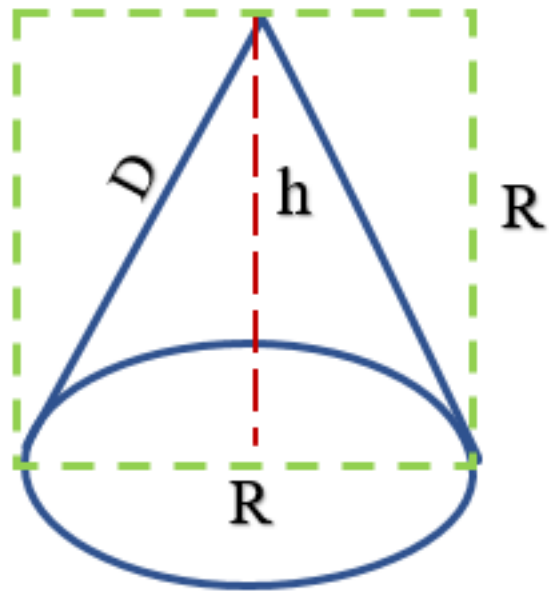
cover created overestimation of area in ArcGIS. To work around this problem, I created a raster (30mx 30m) of the entire mountain. I transformed the shapefiles into rasters of similar extent with the same pixel size. I reclassified the output raster where 0 equaled non-snow cover and 1 equaled snow cover. I summed the number of cells equal to 1 and multiplied by 900-m<sup>2</sup> to give the total area of snow cover. I created a second variable by calculating the percentage of snow area. To increase efficiency, I recreated this same process using the ModelBuilder feature in ArcGIS Pro. (Fig. 3).



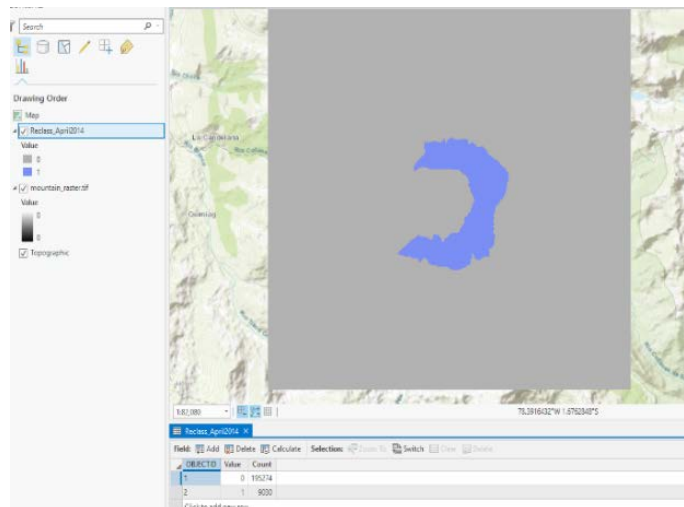
**Figure 29:** ModelBuilder showing the steps used to create the rasters used to measure snow area cover.

## Surface area snow calculations

A planer square area is adequate if the area measured was flat; however, this mountain has a far larger surface area than a planer representation characterizes (Fig. 4). To increase accuracy of these calculation, it was necessary to consider the elevational gradient of the mountain. I used a DEM to inspect slope values, and noted that the sides of the mountain were generally between 50 and 40 degrees. I used the pixel size of the DEM and Pythagorean theory, to calculate the length of the hypotenuse of 30m pixel slanted at 45 degrees. ( $1/2R = 30$ ,  $H = 30$  and the hypotenuse equal 42.42 and the outside angle = 45). Lastly, I multiplied the total number of snow covered pixels by 42.42 to estimate surface area of the inclined pixel. I created a vector polygon that would reflect the area of the volcano ( $169 \text{ Km}^2$ ) and converted into a 30-meters resolution raster of value 0. I ran the ModelBuilder model described in the methods section for



**Figure 4.** Green represents a right triangle of side length  $R = 30\text{--m}$ . Blue cone represents the shape of the mountain.  $D$ , the hypotenuse of the right triangle has a length ( $D$ ) different to the length of right triangle ( $R$ ).



**Figure 5.** Raster of snow cover versus total area of the volcano raster

all the snow cover area. The resulted raster with the value of 0 reflected the area not cover by snow, while a value of 1 represents the area cover by snow. Figure 5 shows an example of how results look in ArcPro.

### Precipitation data

The precipitation and temperature data were downloaded from the website of the Ecuadorian National Institute of Meteorology and Hydrology (INAMHI). The INAMHI has dozens of weather and monitoring stations around the country, some of which are only to record precipitation, but unfortunately, not in the Altar. Instead other weather stations were chosen based on: altitude, distance from the volcano, amount of data available and station type (Figure 6). The data available only



covered the months from January 1991 to December 2012. The precipitation dataset was gathered from the Cotopaxi-El Refugio, Cañar, and Cotopaxi Minitrack weather stations and the Alao and Chunchi pluvial monitoring stations.

### Temperature data

The acquisition of the data for temperature was similar as for precipitation. The INAMIHI reports shows average monthly dry temperature. Three out of the five stations that were considered for precipitation were also considered for temperature (Alao and Chunchi only

monitors rainfall). In the case of temperature (unlike precipitation), years with missing data were not discarded, but rather only the available months were introduced in the calculations. As with precipitation, monthly temperature averages were graphed to observe for any monthly or seasonal changes. Table 1 shows the differences among the stations.

I added the data from the season in which the image was taken up to the month in which the image was taken to run the regression. For example, if the image was taken in March of 1991, I added precipitation from October November, December 1990 (the beginning of the wet season) and January February 1991 up until March (when the image was taken). Similarly, if the image was taken in September, I added precipitation from June (beginning of the dry season) up to September of the same year.

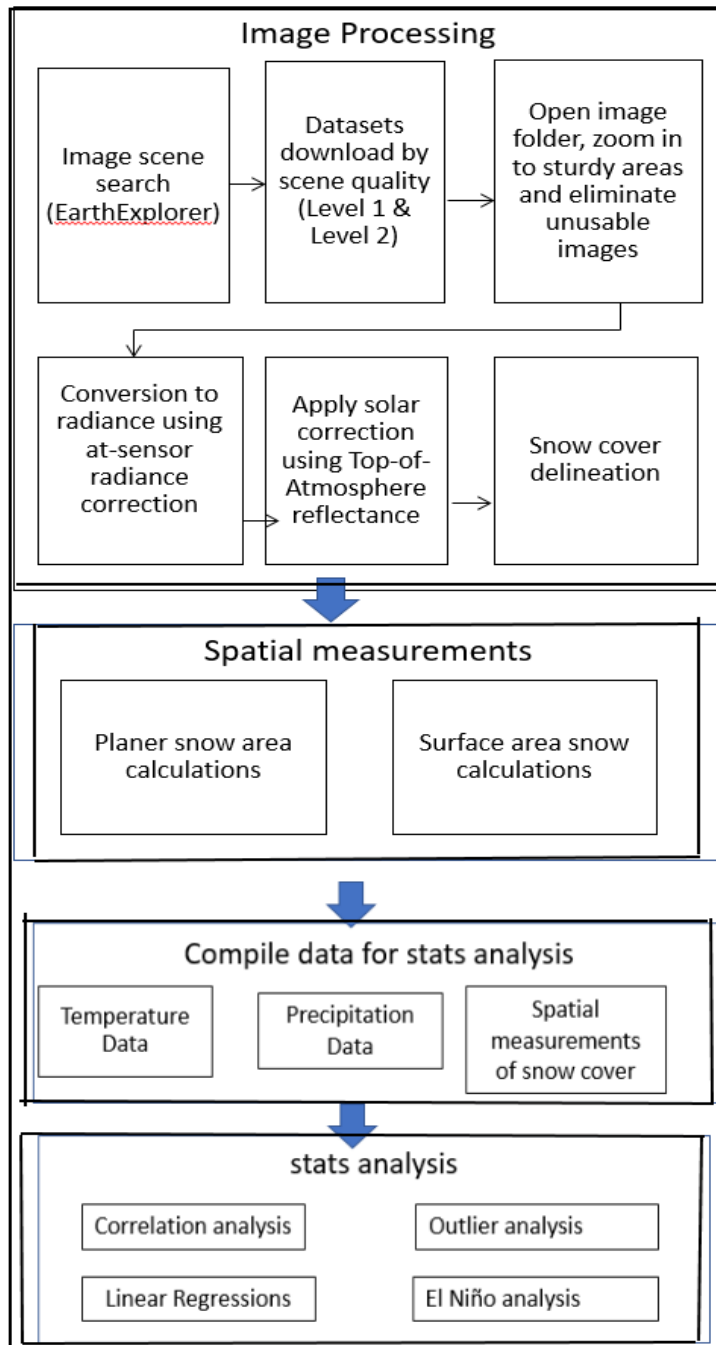
**Table 1.** Weather stations near the Altar used for this project showing their elevation, distance from volcano, the months of data available, and type of station.

	Stations				
	<del>Alao</del>	<del>Cotopaxi Minitrack</del>	<del>Cotopaxi El Refugio</del>	<del>Cañar</del>	<del>Chunchi</del>
<b>Elevation (m)</b>	3,200	3,510	4,800	3,083	2,177
<b>Approx. distance from El Altar (Km)</b>	26	100	107	100	90
<b>Station type</b>	Pluvial gauge	Climatological	Climatological (temporal)	Climatological	Climatological
<b>Months with data available</b>	244 (rainfall only)	159	50	283	264

## Regression Analysis

I used the precipitation and temperature data to create models that might explain in which way and to which degree the change in precipitation and temperature affects the fluctuation in snow

**Table 2.** Workflow of this project



cover. Each regression used the three

different snow cover projections from

the delineation step: plane, percent,

and surface area of cone. The first

models looked at the overall year

around changes. The second and third

models looked at the changes in snow

cover in the dry and wet seasons.

Lastly, I examined the importance of

the findings in the context of strong El

Niño Southern Oscillation event which

had hit the coast of Ecuador during the

timeline of this project. Table 2

shows the workflow followed on this

project from image processing to

statistical analysis for all three

datasets: snow cover, temperature and

precipitation.

# Results

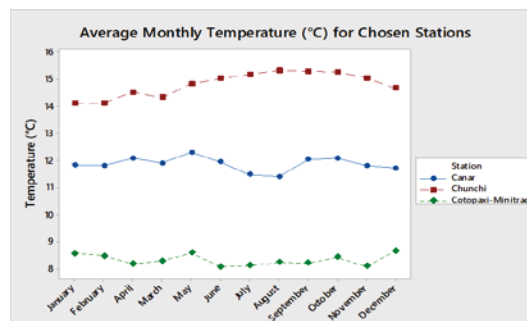
## Temperature

The analysis of temperature across nearby stations yielded high variability among the different weather stations. Elevation is strongly related to the average yearly temperature. For example, the Cotopaxi-Minitrak station (3,510 m) had lower average monthly temperature (Fig. 7), while the Chunchi (2,177 m) station had the highest.

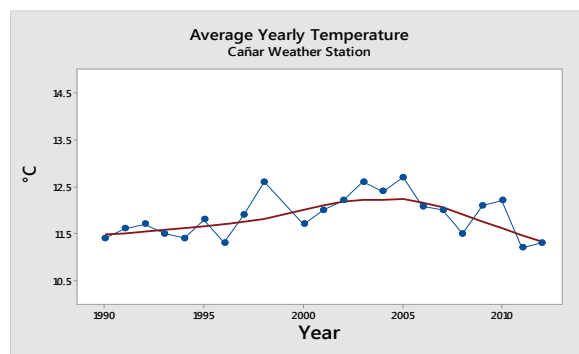
The average monthly temperature of each station did not present significant variability throughout the calendar year. This result was expected because, as mentioned previously, the Altar is located near the equator. Indeed, the line plot does show average yearly temperature varies less than 1 °C year to year. (Fig. 8). Average monthly

temperature during the twenty plus years of data does not show change in average temperature.

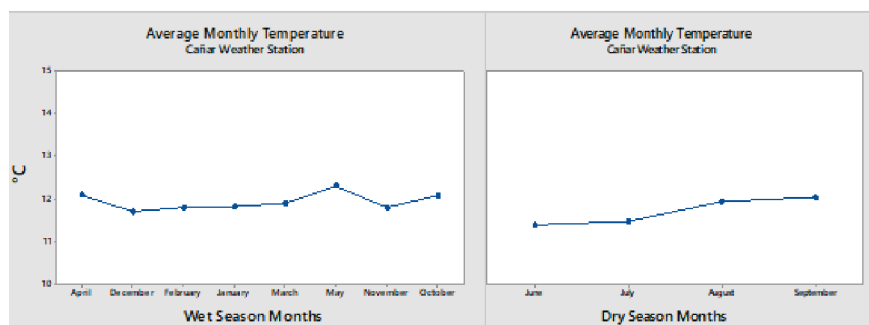
Figure 9 shows the similar average temperature



**Figure 7.** Average monthly temperature for three weather stations: Cañar, Chunchi and Cotopaxi-Minitrak



**Figure 8.** Average temperature in the Cañar weather station. 1990- 2012.

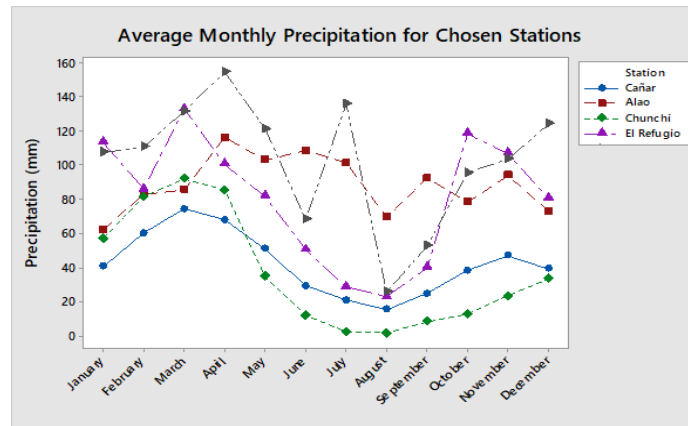


**Figure 9.** Average monthly temperature for the wet and dry seasons in the Cañar weather station. 1990-2012.

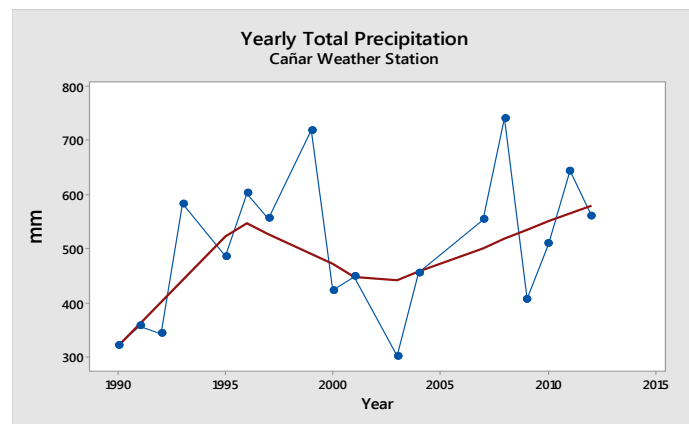
between the wet and the dry season. Based on the previous results and the conditions stated in the methods section, I chose the Cañar station to use for the next steps in this project.

## Precipitation

Analysis of average precipitation in weather stations showed a pattern of considerable differences across all localities. Stations located at higher elevations received higher average precipitation on a yearly basis. El Refugio is the highest elevation station and appeared most geographically similar to the Altar. Unfortunately, data from this station are very limited. The same can be said about the Cotopaxi-Minitrack station and, to a lesser degree, about the Alao and Chunchi stations (Fig.10). Yet, due to its closeness to the volcano (26 km), the Alao station was

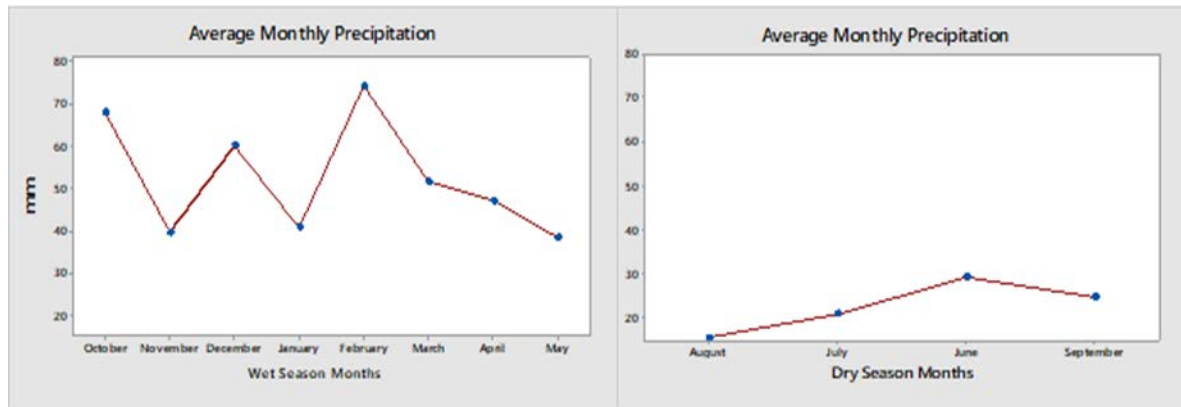


**Figure 10.** Average monthly precipitation in the Chunchi, Alao, Cotopaxi Minitrack, El Refugio, and Cañar. 1990-2012



**Figure 11.** Average yearly precipitation at the Cañar station. 1990-2012

chosen for the regression models. Precipitation data from the Cañar station were used only when dates from Alao's data were not available. Average yearly precipitation shows a significant fluctuation from 1990 to 2012 (Fig. 11). Unlike temperature, the difference in precipitation is significantly different between the wet and dry season, confirming the need to separate the



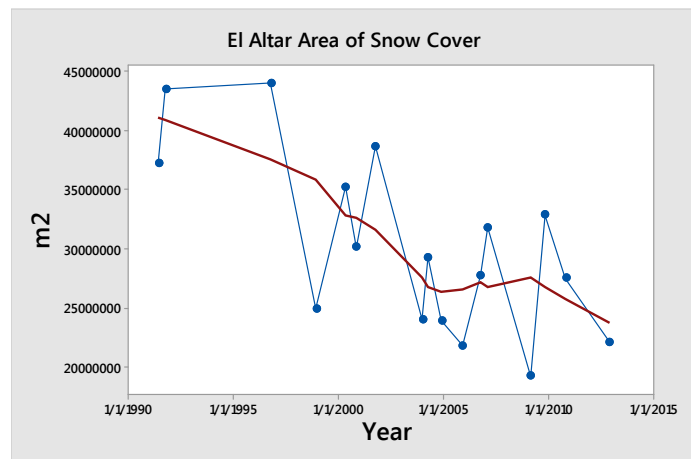
**Figure 12.** Data on average precipitation in the Cañar station segregated by wet and dry seasons. 1990-2012

months of October to May (Wet Season) and June to September (Dry Season) for the regression models (Fig. 12).

### Snow Cover Change

Delineated snow cover shows a decline in amount of snow cover in the volcano (Fig. 13). A total of 32 cloud free images of the volcano were analyzed. The images covered the months from March 1979 to January 2018, evenly distributed in the wet and dry season.

Figure 14 depicts snow cover in the dry



**Figure 13.** Total area of snow cover using the surface of cone projection. 1979-2018.

season. For the first three images (from 1986 to 1996) there is a slight fluctuation but the snow cover but no overall change. Starting with the 2001 image there is a decline, which matches the decrease in precipitation that started in 1999 (followed by a steep decline). The slight increase in



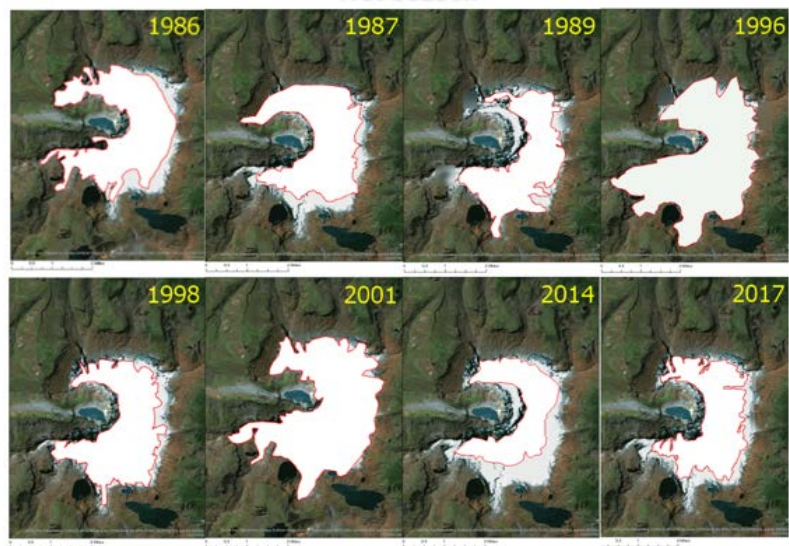
snow cover on the image from 2012 also matches the increase in precipitation which started in 2010.

In the wet season images (Fig. 15), the 1996 and 2001 coverage shows also a match with the peaks in the precipitation data. The precipitation data also show a peak in 2009, matching an increase in snow cover as well.

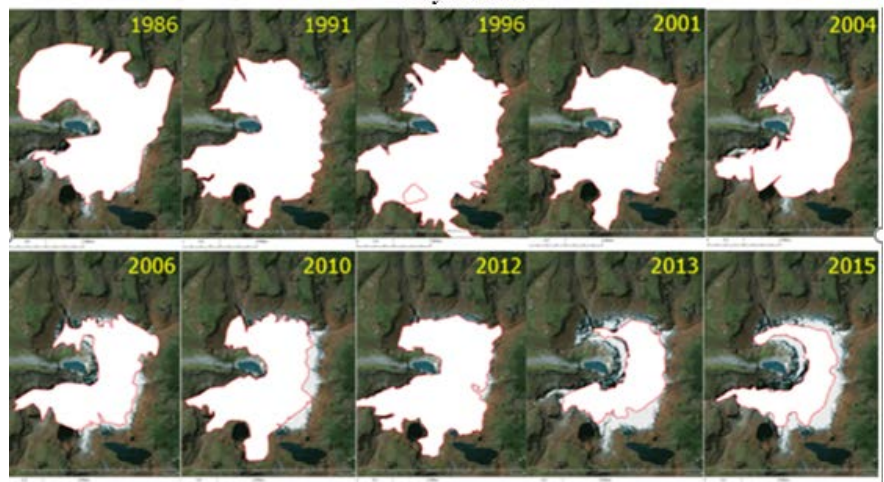
### Calculating Surface Areas

The area of the volcano covers 205,304 pixels of 30m each. Each snow delineation was converted into raster to create three different projections. i) Area of snow cover projection the number of snow by counting

pixels representing snow cover. ii) Measure of surface area to correct for elevation (surface of cone projection). ii) The percentage projection shows percentage of pixels within the study area.



**Figure 14.** Snapshots of the snow cover delineation from images taken during the dry season. 1986-2017. Basemap credit: ESRI.



**Figure 15.** Snapshots of the snow cover delineation from images taken during the wet season. 1986-2017. Basemap credit: ESRI.

It is important to note the significant difference between the planer and the surface of cone. The dry season dataset shows the highest difference, or decline, between 1991 and 2012.

## Linear Regressions

Model 1: Year around

The Surface of area of cone, which depicts a more realistic picture of area covered by snow, produced the strongest model for the entire year. With the surface area of cone method,

**Table 3.** Data used to run the linear regression models. Snow cover area in the three different projections segregated by wet and dry season.

Dry Season				Wet Season			
Date	Planer square meter	Percent	Surface area of cone	Date	Planer square meter	Percent	Surface area of cone
7/1/1991	26,904,600	15%	53,792,950	5/1/1991	18,581,400	10%	37,151,577
8/1/1996	29,860,200	16%	59,702,364	10/1/1991	21,765,600	12%	43,518,054
6/1/1997	10,616,400	6%	21,226,388	10/1/1996	21,998,700	12%	43,984,113
6/1/1999	18,308,700	10%	36,606,342	12/1/1998	12,454,200	7%	24,900,878
7/1/2000	19,463,400	11%	38,915,044	5/1/2000	17,618,400	10%	35,226,158
9/1/2001	24,082,200	13%	48,149,854	11/1/2000	15,052,500	8%	30,095,908
9/1/2002	21,382,200	11%	42,751,485	10/1/2001	19,338,300	11%	38,664,920
9/1/2004	19,323,900	12%	38,636,128	1/1/2004	12,001,500	7%	23,995,751
7/1/2006	16,192,800	9%	32,375,820	4/1/2004	14,610,600	8%	29,212,375
7/1/2007	23,885,100	13%	47,755,773	12/1/2004	11,942,100	6%	23,876,987
9/1/2007	22,572,000	12%	45,130,367	12/1/2005	10,879,200	6%	21,751,829
8/1/2008	22,312,800	12%	44,612,123	10/1/2006	13,864,500	8%	27,720,626
9/1/2009	12,525,300	7%	25,043,035	2/1/2007	15,879,600	9%	31,749,609
9/1/2010	18,825,300	10%	37,639,230	3/1/2009	9,584,100	5%	19,162,411
6/1/2011	13,387,500	7%	26,766,914	11/1/2009	16,427,700	9%	32,845,478
6/1/2012	11,617,200	6%	23,227,383	11/1/2010	13,727,700	8%	27,447,108
7/1/2012	11,293,200	6%	44,583,332	12/1/2012	11,027,700	6%	22,048,739

precipitation and temperature show the lowest P-values and highest F-values, in comparison with the other methods. For all three outcomes, precipitation is the variable which exerts a largest effect and is the most statistically significant predictor.

The three models of the full year show precipitation levels strongly influence snow coverage.

Also, based on these statistical analyses, the surface area of the cone is a more accurate way to

analyze snow cover and to use it to explain variance in temperature and precipitation in the system (Table 3). The Pearson linear regression values explain about 20 percent of the variation in snow cover.

Residuals for all three methods suggest the responses (area of snow cover) are normally distributed. The residuals analysis also tells us the data are distributed randomly.

The same four points appear as outliers in all three methods. These outliers come from data points taken from a different weather station. These data points were taken from a different station because of missing data in the Cañar weather station. Three out of the four outliers are about 0.5 standard deviations from the mean and only one (data point from 1979) is more than two standard deviations away from the mean.

#### Model 2: Wet Season

The wet season model produced the highest  $R^2$  but not adjusted  $R^2$ . Unlike the previous model, the wet season seem to be highly influenced by temperature while precipitation seems to have very little influence, if at all (See table 4). Also, unlike the previous model, in this second model the planer  $m^2$  and the surface of area of cone are not only equally accurate, but identical.

The normal probability plot shows the data in this model are also normally distributed. Similarly, to the previous model, the outliers are data from a different weather stations. There are not outliers from data points gathered at the Cañar weather station.

#### Model 3: Dry Season

The dry season model does not show significant relations between temperature and precipitation and the snow cover in all of the three methods. The p-values are higher than 0.05 and therefore not statistically significant (Table 4).

The residuals analysis also shows the data are normally and randomly distributed. Outliers are found to be those from different weather stations.

**Table 4.** Results from the linear regression models for the entire year, wet season and dry season.  $R^2$ ,  $R$ -sq(adj), P-values, F-values and T-values

		Model type	R-sq	R-sq(adj)	Temperature			Precipitation		
					P-Value	F-Value	T-Value	P-Value	F-Value	T-Value
Model 1: Whole year	Planer		20.4%	15.3%	0.035	4.85	-2.20	0.022	5.86	-2.42
	Percentage		17.9%	12.6%	0.057	3.92	-1.98	0.030	5.18	-2.28
	Surface Area		25.5%	20.7%	0.016	6.54	-2.56	0.009	7.76	-2.79
Model 2: Wet Season	Planer		29.4%	19.3%	0.033	5.62	-2.37	0.222	1.63	-1.28
	Percentage		26.1%	15.5%	0.048	4.67	-2.16	0.230	1.57	-1.25
	Surface Area		29.4%	19.3%	0.033	5.62	-2.37	0.222	1.63	-1.28
Model 3: Dry Season	Planer		15.4%	3.3%	0.304	1.14	-1.07	0.262	1.37	-1.17
	Percentage		11.2%	0.0%	0.434	0.65	-0.81	0.315	1.09	-1.04
	Surface Area		25.6%	15.0%	0.093	3.24	-1.80	0.241	1.50	-1.22

## Discussion

Temperature and precipitation have unique and salient effects on snow coverage. The changes in snow cover captured by Landsat offer an opportunity to evaluate how these variables interact and better understand what roles they play in maintaining the hydrological reservoir on El Altar.

This study found no change in temperature's monthly variability or a significant trend on average yearly temperature. However, there was a strong relationship between elevation and lower average temperature. Assessing climate causing variables in the Andes, including precipitation and drought, is very difficult. In this paper, I gathered data from similar and adjacent areas to the volcano Altar and found high variability among them. The considerable differences among weather stations, none of which are more the 120-km apart from each other, are linked partially to elevation. Determining all the other variables is much more complicated.

El Niño-Southern Oscillation (ENSO) cycles have a complex influence on Ecuador's climate. ENSO events explain some of the climatic patterns in the Altar and in the Andes in general. The warming of the Pacific Ocean during El Niño, brings episodes of extreme precipitation, especially in the coastal region. La Niña is characterized by especially cool ocean temperatures and considered to be related to episodes of drought. Although the effects of the ENSO cycle are well known in the coastal region, it is not as consistent for the Andean region due to other influencing factors such as elevation. Some research suggests that ENSO events enhance drought intensity and prevalence in the Andean mountains (Serrano-Vicente et al. 2017). With climate change, it is expected that the intensity and frequency of El Niño events will continue to increase (Bendix et al. 2011). Therefore, it is important to understand better how these variables interact.

In this paper years of El Niño and La Niña events do not directly align with either increased or decreased snow cover. The poor alignment of ENSO events and snow coverage suggests El Altar is influenced by more than one weather regime. The hydrological system in the volcano involves spatial and temporal climatic variables of precipitation which are part of the global atmospheric circulation mechanisms and are influenced by events occurring by the ocean. Isolating these variables to study their individual influence is extremely difficult. Another reason for the poor correspondence between ENSO and precipitation on el Altar is that ENSO events are not all the same, they vary in location of highest impact, intensity and frequency. In addition to the severity of the events, researchers have identified varied spatial distribution of severity across events. Some ENSO events might heavily affect one area versus another, and from one of the events to the next. This is what authors have called the different ENSO "flavors" (Serrano-Vicente et al. 2017). For example, in the 1982-3 and the 1997-8 El Niño events, the central and southern areas

of the Coastal regions were the most affected, while in the event 2015-6 the largest damage was in the central and northern areas of the coastal region. Depending on which area is more affected during a particular event, ENSO may have more or less impact in the precipitation and snow cover of the Altar. Finally, ENSO events may start in a similar manner but they end in many different conditions. The time between when a ENSO event occurs and when the effects are felt also plays a role. There is a time lag between the ENSO and when the effects are manifested at the Altar. This temporal separation between cause and effect adds complexity in trying to explain specific links. Threshold effects may also play a part in the relations between precipitation and snow cover. It is possible snow cover decline might only be visible when in years when el Niño is strong or very strong. These factors may be why the precipitation data do not explain more of the variance in snow cover.

Understanding what influences the fluctuation in precipitation and ENSO caused droughts is important to the natural systems of the National Park Sangay and to the people living in the western plain below the volcano. As this project shows, gathering exact data from the precise area is pivotal to increase accuracy. Snow cover is difficult to quantify because of the shape of the volcano. The model created in this project which closer resembles the shape of the volcano is the one which explains correlation the best. This means that it is important to model the mountain's surface area to get a better sense of the how much precipitation influences snow cover. Accurate data is critical to modeling efforts on precipitation in the volcano to quantify the effects of El Niño and La Niña in the Altar. With a low average temperature year around, the Altar, especially at highest elevations, may be able to hold to snow cover gained in heavy precipitation periods due to the reasons explained above. In this context, the mountain and its

snow cover may be very resilient to changes until thresholds are crossed. However, when the thresholds are crossed the potential for loss of snow cover are potentially devastating.

More frequent and intense ENSO events can further amplify the loss of snow cover in the Altar, severely affecting the pristine ecosystems of the Sangay National Park, the water resources of the nearby towns, and agricultural lands in the volcano's western slope. Droughts in Ecuador affect agriculture or the production of hydroelectrical power. Excessive precipitation destroys infrastructure and property. This study presents the real possibility that climate change will impact the Altar-and other Ecuadorian mountains- in a significant way.

## Conclusion

The analysis of Landsat images analyzed in this project show a decline of snow cover in the Altar (1979-2018). While temperatures were closely aligned with elevation and thus different between various monitoring stations, none of the weather stations showed signs of increase in the average temperature. However, there was significant variation in the precipitation. Regression modeling suggest that precipitation explains more variance throughout the year while temperature is especially significant in the wet season that while temperature had no variance, it was a better variable to explain snow cover in the wet season than precipitation was. Overall temperature and precipitation explained about 20 % of the variance in snow cover. Climate in Ecuador is heavily influenced by ENSO. El Niño strongly impacts precipitation in the Andean mountains, although the impact in the Altar, specifically, is not clear. These connections are difficult to make due to thresholds and spatial temporal manifestation to cause and effect. Climate change is changing the frequency and intensity on ENSO events. These changes will

likely continue to force the decrease on snow cover which will be devastating to the people and ecosystems depending on water from the volcano.

For further research this type of study could be improved by completing the data to include all the months throughout the time frame of the study (39 years in the case of this paper). Such an inventory would increase the precision of the relations between snow cover and temperature and precipitation. However, large amounts of cloud cover in the area make this task difficult. For this study, hundreds of images were observed and most of them discarded due to high cloud cover. A more detailed study will also require precipitation and temperature data gathered at the volcano, preferably data at different elevations to account for topographical differences.

Understanding climate patterns in this area is very complex because it is a site where several systems meet, but accurate *in-situ* measurements can better minimize external factors because precipitation tends to be localized. It is important to lobby the Ecuadorian government or to contact national or international organizations to install weather stations in all, or at least most, of the Andean Mountains

Lastly, results were discussed in the context of ENSO events and drought patterns identified in the literature. This project identified a significant decrease in the areas of snow cover, and detected high fluctuation in precipitation with little or none change or fluctuation in temperature. I also identified a strong relationship between precipitation and snow cover. The significance of this finding is given by the known relationship between ENSO events and drought and it suggests the possibility of strong impact in snow cover in the Altar.



## Bibliography

- Andes, Ecosystem sentinels for climate change? Evidence of wetland cover changes over the last 30 years in the tropical. 2017. "Dangles, Olivier; Rabatel, Antoine; Kraemer, Martin; Zeballos, Gabriel." *PLoS One* 1-22.
- Asfaw, Amogne, Belay Simane, Ali Hassen, and Amare Bantider. 2018. "Variability and time series trend analysis of rainfall and temperature in northcentral Ethiopia: A case study in Woleka sub-basin." *Weather and Climate Extremes* 29-41.  
<https://doi.org/10.1016/j.wace.2017.12.002>.
- Bendix, Jörg, Katja Trachte, Enrique Palacios, Rütger Rollenbeck, Dietrich Göttlicher, Thomas Nauss, and Astrid Bendix. 2011. "El Niño meets La Niña-- Anomalous Rainfall Patterns in the "Traditional" El Niño Region of Southern Ecuador." *Erdkunde* 151–167.  
doi:10.3112/erdkunde.2011.02.04.
- Benhanifia, K, A Bekradda, and S. Smith. 2002. "Multitemporal Remote Sensing and Geographic Information Systems: A Useful Tool for Detecting and Mapping Forest Changes." *Surveying and Land Information Systems* 62 (3): 171-177.
- Brown, Ross D. 2000. "Northern Hemisphere Snow Cover Variability and Change, 1915–97." *American Meteorological Society* .
- Chevallier, Pierre, Bernard Pouyaud, Marie Mojaïsky, Mikhaïl Bolgov, and Oliver Olsson. 2014. "River flow regime and snow cover of the Pamir Alay (Central Asia) in a changing climate." *Hydrological Sciences Journal* 1491–1506.
- Climate Change Knowledge Portal. 2018. *Ecuador Dashboard*. Accessed 2018.  
[http://sdwebx.worldbank.org/climateportal/countryprofile/home.cfm?page=country\\_profile&CCode=ECU&ThisTab=ClimateBaseline](http://sdwebx.worldbank.org/climateportal/countryprofile/home.cfm?page=country_profile&CCode=ECU&ThisTab=ClimateBaseline).
- Country Watch. 2017. *Ecuador Country Review*. Yearly country review , Houston, Texas: CountryWatch, Inc. <http://www.countrywatch.com>.
- Dahlke, Carola, Alexander Loew, and Christian Reick. 2012. "Robust Identification of Global Greening Phase Patterns from Remote Sensing Vegetation Products." *Journal of Climate* 25: 8289-8307. doi:DOI: 10.1175/JCLI-D-11-00319.1.
- Delbart, Nicolas, Samuel Dunesme, Emilie Lavie, and Malika Madelin et Régis. 2015. "Remote sensing of Andean mountain snow cover to forecast water discharge of Cuyo rivers." *Journal of Alpine Research* 1-15. doi:10.4000/rga.2903.
- Di Liberto, Tom. 2014. *The Walker Circulation: ENSO's atmospheric buddy*. August.  
<https://www.climate.gov/news-features/blogs/enso/walker-circulation-ensos-atmospheric-buddy>.

- Duran-Alarcon, Claudio, Caroline M. Gevaert, Cristian Mattar, Juan C. Jimenez-Munoz, Jose Pasapera-Gonzales, Jose A. Sobrino, Yamina Silvia-Vidal, Octavio Fashe-Raymundo, Tulio Chavez-Espiritu, and Nelson Santillan-Portilla. 2015. "Recent trends on glacier area retreat over the group of Nevados Caullaraju-Pastoruri (Cordillera Blanca, Peru) using Landsat imagery." *Journal of South American Earth Sciences* 59: 19-26.
- Gilles, Carbonnier, Humberto (Ed.) Campodónico Sánchez, Tezanos, and Sergio Vázquez. 2017. "Alternative pathways to sustainable development: Lessons from Latin America." *International Development Policy*.
- Gómez, Cristina, Joanne C. White, and Michael A. Wulder. 2016. "Optical remotely sensed time series data for land cover classification: A review." *Journal of Photometry and Remote Sensing* 116: 55-72. doi:10.1016/j.isprsjprs.2016.03.008.
- Harris Geospatial Solutions, Inc. 2018. March. Accessed 2018. <http://www.harrisgeospatial.com>.
- Hentschel, Jesko, Jean Olson Lanjouw, Peter Lanjouw, and Javier Poggi. 2018. "Combining Census and Survey Data to Trace the Spatial Dimensions of Poverty: A Case Study of Ecuador." *The World Bank Economic Review* 147-165.
- INEC Ecuador. 2018. *Instituto Nacional de Estadísticas y Censos*. Accessed 2018. <http://www.ecuadorencifras.gob.ec/institucional/home/>.
- IPCC. 2014. "Climate Change 2014 Climate Change 2014: Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Synthesis Report, Geneva, Switzerland.
- Jorgenses, Peter, Carmen Ulloa, and Carla Maldonado. 2006. "Riqueza de plantas vasculares." *Botánica Económica de las Andes* 37-50.
- Kirschbaum, Dalia B., George J. Huffman, Robert F. Adler, Scott Braun, Kevin Garrett, Erin Jones, Amy McNally, et al. 2017. "NASA's Remotely Sensed Precipitation. A Reservoir for Applications Users." *American Meteorological Society* 1169-1183. doi:10.1175/BAMS-D-15-00296.1.
- La Frenierre, Jeff, and Bryan G Mark. 2017. "Detecting Patterns of Climate Change at Volcán Chimborazo, Ecuador, by Integrating Instrumental Data, Public Observations, and Glacier Change Analysis." *Annals of the American Association of Geographers* 979-997.
- Linde, Jonathan, and Stefan Grab. 2011. "The changing trajectory of snow mapping." *Progress in Physical Geography* 139-160.
- Maynard, Jonathan, and Jason Karl. 2017. "A hyper-temporal remote sensing protocol for high-resolution mapping of ecological sites." *PLoS One*. doi:doi.org/10.1371/journal.

- Mendieta Muñoz, Rodrigo, Monica Raileanu-Szeles, Pablo Beltran Romero, and Juan Piedra Peña. 2015. "Explaining the regional economic heterogeneity in Ecuador." *Economic Sciences* 8: 399-406.
- Ministerio de Turismo de Ecuador. 2018. *Ecuador Travel*. <https://www.turismo.gob.ec/>.
- Mishra, Bhogendra, Mukand S. Babel, and Nitin K. Tripathi. 2013. "Theoretical & Applied Climatology." *Analysis of climatic variability and snow cover in the Kaligandaki River Basin, Himalaya, Nepal* 681–694.
- Poveda, G., and K. Pineda. 2009. "Reassessment of Colombia's tropical glaciers retreat rates: are they bound to disappear during the 2010–2020 decade?" *Advances in Geosciences* 107-116.
- Rodwell, Donald, Geoffrey Seltzer, David Anderson, Mark Abbott, David Enfield, and Jeremy Newman. 1999. *An ~15,000- Year Records of El niño- Driven Alluniantion in Sotuhwestern Ecuador*. American Association for the Advancement of Science, Science, New Series. <http://www.jstor.org/stable/2896957>.
- Rosqvist, Gunhild. 1995. "Proglacial lacustrine sediments from El Altar, Ecuador: evidence for late-Holocene climatic change." *The Holocene* 111-117.
- RStudio. n.d. *Download* . Accessed 2018. <https://www.rstudio.com/products/rstudio/download/>.
- Rugel, Emily J., Sarah B. Henderson, Richard M. Carpiano, and Michael Brauer. 2017. "Beyond the Normalized Difference Vegetation Index (NDVI): Developing a Natural Space Index for population-level health research." *Environmental Research* 159: 474–483.
- Serrano-Vicente, S.M., Aguilar· E., R. Martínez, N. Martín-Hernández, C. Azorin-Molina, A. Sanchez-Lorenzo, A. El Kenawy, et al. 2017. "The complex influence of ENSO on droughts in Ecuador." *Springer* 405-427. doi:DOI 10.1007/s00382-016-3082-y.
- Sospedra-Alfonso, Reinel, Joe R. Melton, and William J. Merryfield. 2015. "Effects of temperature and precipitation on snowpack variability in the Central Rocky Mountains as a function of elevation." *Geophysical Research Letters* 42: 4429–4438. doi:10.1002/2015GL063898.
- Stigter, Emmy, Niko Wanders, Tuomo Saloranta, Joseph Shea, and Marc Bierkens. 2017. "Assimilation of snow cover and snow depth into a snow model." *The Cryosphere* 1647–1664.
- The World Bank Group. 2018. *Climate Change Knowledge Portal*. Accessed 2018. [http://sdwebx.worldbank.org/climateportal/index.cfm?page=country\\_historical\\_climate&ThisCCCode=ECU](http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisCCCode=ECU).
- U.S. Geological Survey. 2018. *EarthExplorer*. Accessed 2017, 2018. <https://earthexplorer.usgs.gov>.

- . 2018. *Landsat Level-1 Data Products*. March 28. Accessed 2018. <https://landsat.usgs.gov/landsat-level-1-standard-data-products>.
- . 2018. *Landsat Missions*. March 28. Accessed 2018. <https://landsat.usgs.gov>.
- . 2018. *LandsatLook Images*. March. Accessed 2018. <https://landsat.usgs.gov/landsatlook-images>.
- Young, Nicholas E, Ryan S Anderson, Stephen M Chignell, and Anthony G Vorster. 2017. "A survival guide to Landsat preprocessing." *Ecology* 920–932.
- Zhu, Zhe. 2017. "Change detection using landsat time series: A review of frequencies preprocessing, algorithms, and applications." *Journal of Photogrammetry and Remote Sensing* 370–384.